Variation of microfibril angle and its correlation to wood properties in poplars

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Abstract: The microfibril angle of seven poplar clones was determined by using X-ray diffraction technique. Microfibril angle, wood basic density, fiber length, fiber width and cellulose content were assessed for every growth ring at breast height for all sample trees. Significant variation in microfibril angle was observed among growth rings. Mean microfibril angle (MFA) at breast height varied from 7.8º to 28º between growth rings with cambial age and showed a consistent pith-to-bark trend of decline angles. Analysis of variance also indicated that there were significant differences in wood basic density, fiber length, fiber width and cellulose content between the growth rings, which had an increasing tendency from pith to bark. Correlations between MFA and examined wood properties were predominantly large and significant negative (α=0.01), and the coefficients were -0.660 for cellulose content, -0.586 for fiber length, -0.516 for fiber width and -0.450 for wood basic density, respectively. Regression analysis with linear and curve estimation indicated that a quadratic function showed the largest R^2 and the least standard error for describing the relationships between microfibril angle and measured wood properties, and the correlation coefficients were over -0.45 (n=125). The results from this study suggested that microfibril angle would be a good characteristic for improvement in the future breeding program of poplars.

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Introduction

Microfibril angle (MFA) refers to the angle between the direction of the helical windings of cellulose microfibrils in the secondary cell wall of fibers and tracheids and the long axis of the cell (Barnett *et al.* 2004). Variation in MFA in the S_2 layer of the cell wall among individual tracheids and among samples of wood from various positions within the tree stem and among individual trees, has been related to the strength and shrinkage properties of solid wood and to the tensile strength, and tear properties of paper and pulp fibers (Cave 1968; Donaldson 1992; Cave *et al.* 1994; Walker *et al.* 1995). Wood in which the MFA is large has a low Young's modulus and is therefore suitable only for low-grade use, reducing its value as a raw material and its economic value. This problem was not too serious in the past when trees were allowed to reach maturity before being harvested. Increasing demand for timber, pulp and wood products is driving the forest industry towards short-rotation cropping of fast-growing species like *Pinus radiata* and *Populus* hybrids.

Poplars can be used for different forms of processing in the timber industry, in the fiber industry and as a source of energy (Gambles *et al.* 1984; Fang *et al.* 1999). Since poplar clones were introduced to China in the 1970s, poplars have become the major tree species in both plantation forestry and agroforestry systems throughout the south temperate central area of China, an area of roughly 600 000 km^2 (Fang *et al.* 1999). Interest in short-rotation production of various poplar hybrids for fiber and veneer has accelerated greatly in Jianghan Plain and central China during the past decades (Fang *et al.* 2003), in which poplars are relatively short-lived, fast-growing trees that can grow on marginal soils are widely adaptable. The breeding program of poplar trees in China has, in the past, concentrated on selection for such features as growth rate, stem form and crown form. However, recently there has been renewed interest in selection based on wood-quality criteria such as basic density, fiber characteristics and chemical composition. The objectives of this work were to investigate the relationship between MAF and wood properties among poplar trees, and examine the potential in genetic selection for low microfibril angle by estimating the variation in MAF and wood properties.

Materials and methods

Materials

Stem discs were collected from 7 clones produced from cuttings of genetically-select (for growth rate and tree form) poplars, growing in two clonal trials in Hanyuan Forestry Farm, Baoing County, Jiangsu Province, China (33º08'N, 119º19'E). The two trials were planted at the same site

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condition (SI=18 m), but in different years and with various planting densities (Table 1). The seven poplar clones were clone I-69 (*Populus deltoides* Bartr. cv. 'Lux'), I-72 (*P.xeuramaricana* (Dode) Guinier cv. 'San Martino'), NI-80351, a hybrid of I-69 × I-63 (*P. deltoides* Bartr. cv. 'Havard'), and the other four clones (Nanlin-95, Nanlin-895, Nanlin-447 and Nanlin-1388), new hybrids of I-69 × I-45 (*P.xeuramaricana* (Dode) Guinier cv. 'I-45/51'). These seven poplar clones are under consideration for veneer and ground pulp production in China.

Table 1. General characteristics of 7 poplar clones sampled at the same site

Trial number	Clone	Spacing /m	Stand age /a	Tree height /m	DBH /cm
1	NL-80351	4×5	12	22.8	22.5
1	I-69	4×5	12	22.9	20.1
1	I-72	4×5	12	22.9	21.4
2	Nanlin-95	6×6	11	25.7	26.9
2	Nanlin-447	6×6	11	27.0	30.2
2	Nanlin-895	6×6	11	25.1	28.0
2	Nanlin-1388	6×6	11	25.2	26.8

Sampling

The selection of the sample tree was based on the mean DBH (diameter at breast height) and the means of total tree height for each clone in the trials. Diameters at 1.3 m height of all trees in each trial were measured and total height was measured for all trees within 15% of the mean DBH for each trial before sampling. The single trees closest to the means of DBH and height and with good form and vigor were selected for destructive sampling (Table 1). Two trees were sampled for each poplar clone and 14 trees in total were destructively sampled in the study.

Each sample tree was cut at ground level and discs (about 50 mm thick) were collected from the butt, at 1.3 m, 3.6 m and every subsequent 2 m interval up to 21.6 m height. Diameter growth increment was measured for each growth ring on the breast height (at 1.3 m). The discs at breast height for all sample trees and the discs at 0 (butt), 5.6, 9.6, 13.6, 17.6, 19.6 and 21.6 m for I-69, Nanlin-95 and Nanlin-895 were prepared for microfibril angle measurements, and three tangential samples for each growth ring were measured. The finished sample size for MFA measurement was (longitudinally) 15 mm× 5 mm × 1 mm (tangentially) and about 900 samples (chips) were measured in total.

Microfibril angle measurement

The microfibril angle (MFA) was determined by X-ray diffraction technique with the 002 diffraction arcs (D-max/3B diffraction meter). The experimental conditions were developed by Li *et al.* (1997), which were symmetric transmission configuration, nickel-filtered radiation, 40 KV, and 30 mA. Average MFA of the fiber wall layers was then computed using Cave's (1966) formula:

$$\mathrm{MFA}=0.6T \quad (1)$$

where T was the X-ray diffraction parameter, MFA was the microfibril angle.

Wood property measurements

A bark-to-bark strip of wood was cut across the diameter of each disc and strips were cut in a north-south direction. Each strip was first used for determining basic density, and then used for fiber characteristics and cellulose content measurements. Wood properties for each growth ring were only measured for the discs at breast height. Fiber length and fiber width were measured on macerated samples using an image analysis system, and fifty measurements were taken for each parameter. Wood basic density was based on the oven-dry weight/green volume, and was calculated according to the following formula (Cheng 1985):

$$B = 1/[(S/O) - 1] \quad (2)$$

where, B is basic density; S is saturated weight of the sample; O is oven-dry weight of the sample.

Cellulose content was determined based on the national standard for chemical analysis (Monitoring Bureau of National Technology 1981).

Data statistical analysis

Data from this study were analyzed by using SPSS 11.5 (Statistical Product and Service Solutions) software. Tests among growth rings for MFA and wood properties were performed by One-way ANOVA, while bivariate correlations between MFA and wood properties were carried out with Pearson's coefficient. The linear and curve estimation approaches were used for fitting the relationships between MFA and examined properties.

Results

Variation in microfibril angle and wood properties from pith to bark

Microfibril angle

Microfibril angle at breast height varied from 28º to 7.8º among growth rings. Overall MFA decreased from pith to bark in all poplar clones and showed a consistent pith-to-bark trend of decline angles (Fig. 1). Analysis of variance indicated that there were significant differences in microfibril angle among annual growth rings (α=0.01). The highest microfibril angle was observed in the first four growth rings from pith and decreased from pith to bark, while the lowest occurred in the ring 11, which was only about half of the highest. The pith-to-bark trend leveled off around ring 5 from the pith, although this varied from clone to clone.

Cellulose content

The average cellulose content at breast height varied

from 48.0% to 54.6% among growth rings. Overall cellulose content increased from pith to bark in all poplar clones and showed a pith-to-bark trend of increasing cellulose content, although this varied from clone to clone (Fig. 2b). ANOVA indicated that there were significant differences in cellulose content among the rings (α=0.01). The lowest cellulose content was observed in the first two growth rings from pith (below 50%) and increased from pith to bark, while the pith-to-bark trend leveled off around ring 7 from the pith where the mean cellulose content was about 53%.

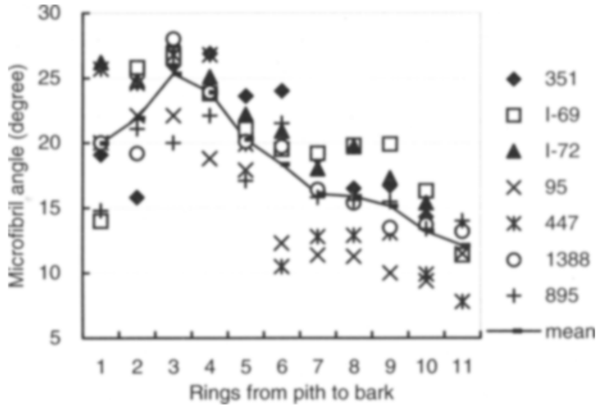

Fig. 1 Variation in microfibril angle at breast height with cambial age for 7 poplar clones

Wood basic density

The average wood basic density at breast height varied from 0.330 g/cm^3 to 0.421 g/cm^3 between growth rings and showed a pith-to-bark trend of increasing wood density, although this varied from clone to clone (Fig. 2a). Analysis of variance showed that there were significant differences in wood basic density among the rings (α=0.01). The lowest wood basic density was observed in the first two growth rings from pith and increased from pith to bark, while the pith-to-bark trend leveled off around ring 6 from the pith where the mean basic density was over 0.390 g/cm^3.

Fiber characteristics

The average fiber length at breast height ranged from 830 μm to 1270 μm between growth rings, while the average fiber width varied from 23 μm to 26 μm (Fig. 2c,d). Overall both fiber length and fiber width increased from pith to bark. The effect of the position of annual rings from pith on fiber length was highly significant (α=0.01). The fiber length was initially quite short near the pith, then steadily increased and showed a tendency to level off at the eighth annual ring. Fiber width also increased with distance from the pith, but significant differences between the growth rings were only found at the 0.05 level, suggesting that cambial age (the position of growth ring) has a less effect on fiber width than on fiber length.

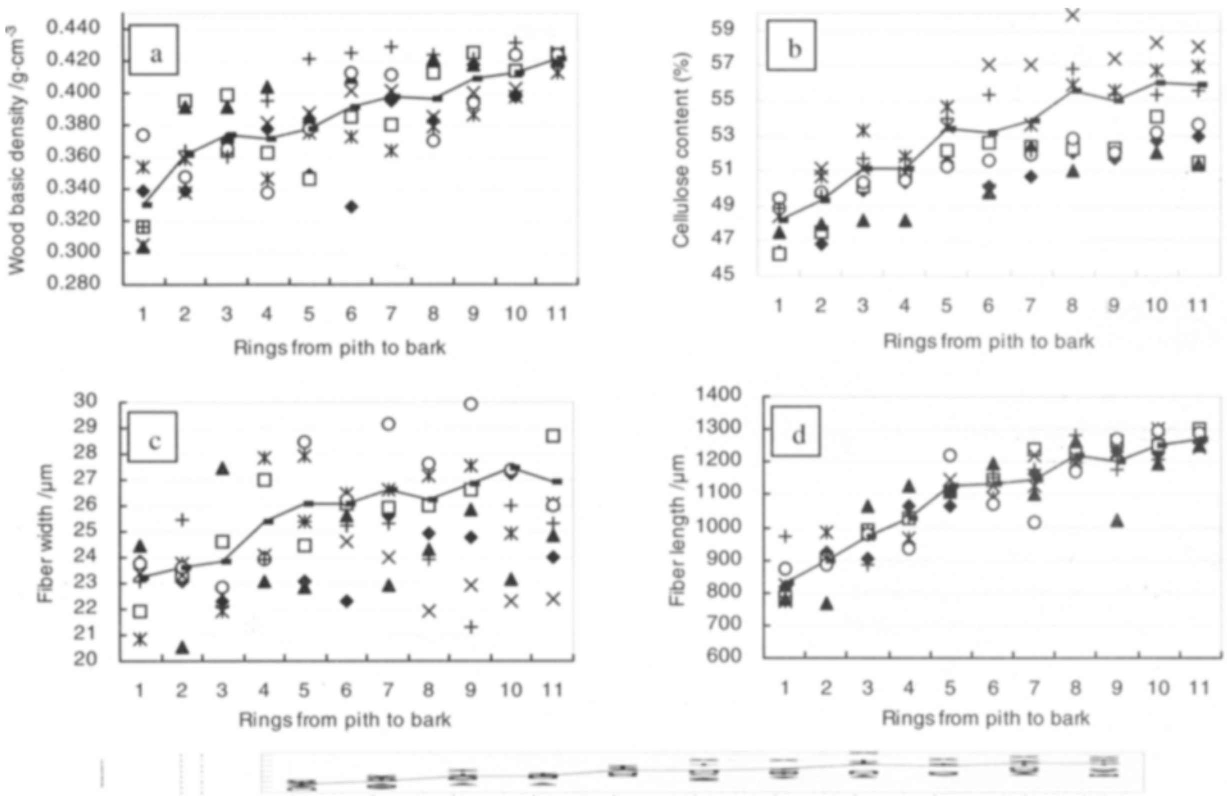

Fig. 2 Variation in cellulose content (a), wood basic density (b), fiber width (c), and fiber length(d) at breast height with cambial age for 7 poplar clones

Correlations with MFA and wood properties

Correlations between microfibril angle and wood properties (wood basic density, fiber length, fiber width and cellulose content) were examined for matched growth rings within a sample of fourteen poplar trees, representing 7 clones, with two trees each clone (n=125). Correlations between MFA and wood properties were high, negative and significant at the 0.01 level, and the coefficients were -0.660 for cellulose content, -0.586 for fiber length, -0.516 for fiber width and -0.450 for wood basic density, respectively (Table 2). The correlations between cellulose content, wood basic density, fiber length and width were also significant at the 0.01 or 0.05 level but positive, and only the coefficients between fiber length and fiber width, and between cellulose content and fiber length were over 0.450, reaching 0.556 and 0.520, respectively.

However, when the data from disc-average values at breast height (n=14) were used for correlation analysis, the correlation coefficients between microfibril angle and wood properties were different from the results based on the ring data (Table 3). MFA was significantly related to cellulose content, fiber length or wood basic density, while the correlation between MFA and fiber width was still negative but non significant at the 0.05 level. Table 3 also showed that only the correlation between wood basic density and fiber length was significant among the examined wood properties.

Table 2. Correlation coefficients between microfibril angle and wood properties based on the data from growth rings at breast height (n=125)

Index	Microfibril angle (MFA) and wood properties				
	MFA	Basic density	Cellulose content	Fiber length	Fiber width
MFA	1.0	-0.450**	-0.660**	-0. 586**	-0.516**
Basic density		1.0	0.223*	0.421**	0.272**
Cellulose content			1.0	0.520**	0.270**
Fiber length				1.0	0.556**
Fiber width					1.0

Notes: ** ----Correlation is significant at the 0.01 level (2 tailed); * ----Correlation is significant at the 0.05 level (2 tailed).

Table 3. Correlation coefficients between microfibril angle and wood properties based on the data from disc-average values at breast height (n=14)

Index	Microfibril angle (MFA) and wood properties				
	MFA	Basic density	Cellulose content	Fiber length	Fiber width
MFA	1.0	-0.559*	-0.757**	-0. 745**	-0.111
Basic density		1.0	0.170	0.686**	0.139
Cellulose content			1.0	0.490	-0.203
Fiber length				1.0	0.268
Fiber width					1.0

Notes: ** ----Correlation is significant at the 0.01 level (2 tailed); * ----Correlation is significant at the 0.05 level (2 tailed).

Relationships between microfibril angle and wood properties

Microfibril angle was significantly correlated with basic density, fiber length, fiber width and cellulose content (α=0.01, n=125). The wood basic density, fiber characteristics and cellulose content decreased as microfibril angle increased. Regression analysis (both linear and curve estimation) also showed that there were significant negative relationships between MFA and examined wood properties (α=0.01, n=125). However, a quadratic function showed the largest R-square (R_2) and least standard error for describing the relationships between MFA and wood properties (Fig. 3), and the correlation coefficients were -0.670 for cellulose content, -0.595 for fiber length, -0.450 for wood basic density (the coefficient and stand error were almost same to the linear model) and -0.551 for fiber width, respectively.

Fig. 3 showed when the microfibril angle is more than 20°, the values of examined wood properties were below the observed means, about 0.39 g·cm^{-3} for wood basic density, 1100 μm for fiber length, 25 μm for fiber width and 51 % for cellulose content respectively. If the relationships between microfibril angle and wood properties are partitioned into juvenile wood (assuming the first six rings define juvenile wood or corewood) and outerwood, microfibril angle is of greater importance in juvenile wood, but become much less significant in the outerwood.

Discussion

Variation pattern in microfibril angle

A general decline in MFA is observed in successive growth rings as the tree matures. Barnett and Bonham (2004) reviewed the early literature, which consistently demonstrated that MFA decreased from higher values in the innermost growth rings to lower values in the outermost ones at all heights in the stem. The patterns of variation in macrofibril angle from pith to bark for seven poplar clones are similar to those reported in *Pinus radiata* (Donaldson 1992; 1993; Donaldson *et al.* 1995) and a range of other

softwood species (Pillow *et al.* 1953; Manwiller 1972; Pedini 1992). The results from our study supported those of Lichtenegger *et al.* (1999) who concluded that microfibril angle in hardwoods was lower than that in softwoods. For instance, microfibril angle in *P. radiata* ranges from 55º at the pith to 9º at the bark (Donaldson 1992), compared to that of *Eucalyptus nitens*, where microfibril angle ranges from 25º at the pith to approximately 14º towards the bark (Evans 1997; Stuart *et al.* 1994), and *Betula pendula*, where microfibril angle ranges from 18º at the pith to about 10º towards the bark (Bonham *et al.* 2001). Our values for hybrid poplars (about 20º at pith and 12º towards the bark) are lower than these for *Populus tomentosa*, where microfibril angle ranges from 23º at the pith to about 16º towards the bark. (Bao *et al.*1998).

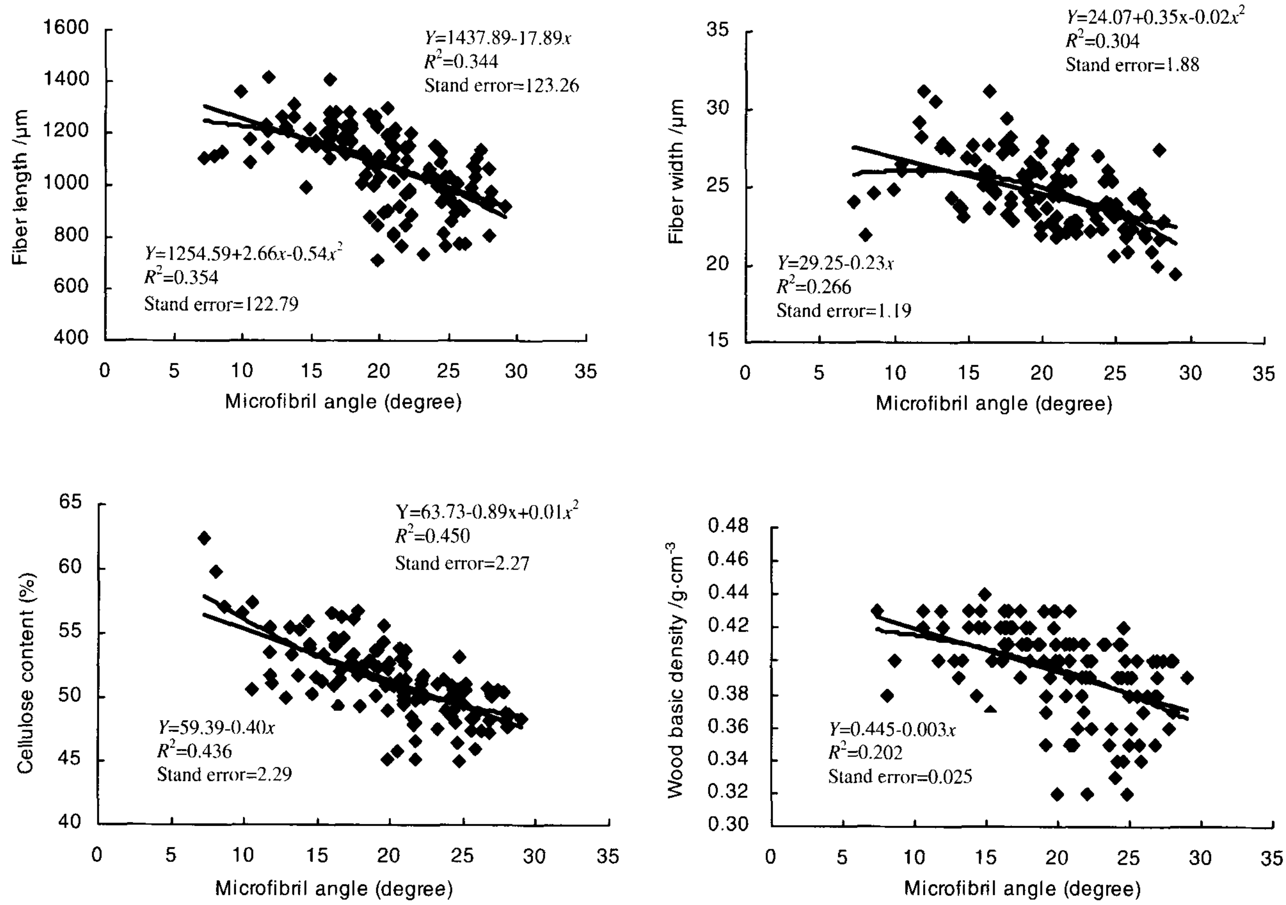

Fig. 3 The relationships between microfibril angle and examined wood properties

Microfibril angle and wood properties

Microfibril angle has two major effects on wood properties (Walker *et al.* 1995; Cave *ET AL.* 1994; Abasolo *et al.* 2000; Barnett *et al.* 2004). First, the stiffness of cell wall increases from pith to cambium as the microfibril angle decreases. Second, longitudinal shrinkage increases with microfibril angle in a highly non-linear manner, and is responsible for some degrade on drying.

The large MFA in juvenile wood confers low stiffness and gives the sapling flexibility it needs to survive high winds without breaking. It also means, however, that timber containing a high proportion of juvenile wood is unsuitable for use as high-grade structural timber. This fact has taken on increasing importance in view of the trend in forestry towards short rotation cropping of fast grown species. These trees at harvest may contain 50% or more of timber with low stiffness and therefore, low economic value (Barnett *et al.* 2004). Although they are presently grown mainly for pulp, pressure for increased timber production means that ways will be sought to improve the quality of their timber by reducing juvenile wood MFA.

There are numerous statements to the effect that wood density is the most important characteristic in determining the properties of wood. This view was recently discussed by Walker & Woollons (1998) who concluded that emphasis on improving wood quality through selection and breeding for higher density and fast growth had the inevitable result that knowledge of the underlying characteristics affecting wood quality has been neglected and remains very incomplete. This view was confirmed by Evans & Ilic (2001) working on *Eucalyptus delegatensis*. They found that MFA together with wood density accounted for approximately 96% of the variation in longitudinal modulus of elasticity

(MOE), with MFA alone accounting for 86% of the variation. Yang and Evans (2003) also found that for *Eucalyptus globulus, E. nitens and E. regnans*, MFA alone accounted for 87 percent of the variation in MOE, while density alone accounted for 81 percent. Together, MFA and density (as Density/MFA) accounted for 92% of the variation in MOE. Thus the influence of MFA on wood stiffness was significantly greater than that of density. In *Cryptomeria japonica* variation of dynamic modulus of elasticity values was explained by the MFA characteristics in each cultivar (Yamashita *et al.* 2000).

Potentials to improve wood quality by modifying microfibril angle in poplars

Selection of any favorable characteristic has benefits for a number of wood properties, with the overall gain depending on the characteristic sought for improvement and its effects on all wood properties. Zhang *et al.* (2004) reported that selection for tree volume growth in white spruce would lead to a decrease in wood density and veneer stiffness. There is sufficient circumstantial data to suggest that an improvement in one characteristic will benefit the other (Walker *et al.* 1995; Dickson *et al.* 1997). Saka (1984) reported that the correlation between microfibril angle and lignin content was strongly positive and the correlation coefficient reached 0.73. Evans *et al.* (2000) found that in *E. nitens* there is strong inverse correlation between MFA and density over a few growth rings but that the relationship was not valid over larger distances. The results from this study confirmed that microfibril angle was strong negatively correlated with basic density, fiber length, fiber width and cellulose content, and the correlation coefficients were over 0.45 (n=125).

Donaldson and Burdon (1995) reported there were significant variations in MFA between trees of radiata pine, and microfibril angle showed a clonal repeatability of 0.7 and estimated coefficient of variation among clones of 8%, which had good potential for improvement by selective breeding. A decrease of 5º in the MFA is a realistic target and would be accompanied by 0.5 mm increase in fiber length for sugi tree (Hirakawa *et al.* 1995). Some reported results indicated that there was a great variation both in microfibril angles (Yang and Fang 2004) and some wood properties (Klasnja *et al.* 2003; Fang *et al.* 2003) at the breast height among poplar clones (α=0.05), suggesting the potential for improvement by selection for low microfibril angle. Therefore, microfibril angle would be a good characteristic for improvement in the future breeding program of poplars. To search more widely does not mean that the benefits of previous identification or selection for density and other wood properties should be abandoned; rather that selection of clones with small microfibril angles should come from that population. Such selection need not be exclusive and should include the screening to remove clones with undesirable traits.

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